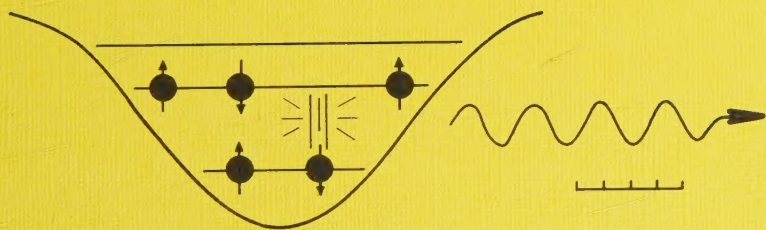


GAMMA-RAY SPECTROSCOPY WITH RADIATIVE
CAPTURE AND NUCLEON TRANSFER REACTIONS

PETER EKSTRÖM



LUND 1975



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1. INTRODUCTION

The ultimate goal in the study of nuclear physics is to account for the properties of complex nuclei in terms of the interactions between nucleons. Such a general microscopic description of the nucleus, however, does not exist today. We have to confine ourselves to more phenomenological models, which are valid for a limited number of nuclei.

In the shell model each nucleon is assumed to move independently in the average central field that describes the short-range interaction with all the other nucleons. The name shell model is derived from the fact that independent Fermions moving in a central field exhibit some shell structure due to the Pauli exclusion principle.

The total wave function of the nucleus is obtained by taking antisymmetric products of single particle wave functions. This description of the nucleus, however, is not complete: A residual interaction between the particles has to be taken into account. The residual interaction, which is often chosen with very simplifying assumptions, is treated as a perturbation. Shell model calculations taking configuration mixing into account involve quite lengthy numerical calculations (resulting, for example, from the diagonalization of very large matrices) and have therefore to be performed with rather powerful computers.

The shell model with a spherically symmetric central potential does not, however, give a good description for all nuclei. In several regions (far away from closed shells) the existence of nuclear deformations is indicated by large electric quadrupole moments. The spectra of these deformed nuclei can most easily be described in terms of rotational bands. In this model of a rotating deformed nucleus (the Nilsson model) the wave functions of the intrinsic states are taken to be those of nucleons moving in a deformed potential. On each such intrinsic state one can build a band of states (rotational band) with the same

intrinsic structure by letting the nucleus rotate around an axis perpendicular to its symmetry axis.

Some nuclear states are best described by letting the nuclear shape perform harmonic oscillations around a spherical or deformed shape (collective vibrations).

It is the object of experimental nuclear spectroscopy to provide the theorists with reliable data with which they can compare their predictions. Such data may be: excitation energies E_x and spins/parities J^π of levels, γ -ray transition probabilities (the calculation of which requires knowledge of lifetimes, branching ratios and multipole mixing ratios), log ft-values of β -decays, spectroscopic factors for nucleon transfer reactions, magnetic dipole moments and electric quadrupole moments.

This thesis consists of the following papers:

- I. THE ENERGY LEVELS OF ^{45}Sc UP TO 3 MeV FROM THE $^{44}\text{Ca}(p,\gamma)^{45}\text{Sc}$ REACTION
(together with B Erlandsson, A Marcinkowski and J Tillman)
Zeitschrift für Physik 252 (1972) 189
- II. ENERGY LEVELS OF ^{24}Na FROM THE $^{23}\text{Na}(d,p\gamma)^{24}\text{Na}$ REACTION
(together with J Tillman and L Carlén)
Nuclear Physics A210 (1973) 458
- III. STUDY OF ^{29}Al WITH THE $^{26}\text{Mg}(\alpha,p\gamma)^{29}\text{Al}$ REACTION
(together with J Tillman)
Nuclear Physics A230 (1974) 285

An elementary presentation of the methods and tools used in the work is presented in section 2, and a summary of the papers is given in section 3.

2. EXPERIMENTAL TECHNIQUES AND EQUIPMENT

2.1 Accelerators

The work reported in this thesis has been performed with Van de Graaff accelerators (VdG:s). A single stage VdG consists of three main parts:

- (i) the pressurized tank
- (ii) the generator (driving motor, moving belt, belt charge power supply and high voltage electrode) and
- (iii) the acceleration tube with an ion source.

The ion source is situated in the high voltage electrode and it produces positive ions (e.g. protons, deuterons or α -particles), which are accelerated down the acceleration tube by the electrostatic field created by the positively charged high voltage electrode.

The accelerated ions are transported through the evacuated beamline (pressure $< 10^{-5}$ torr) with the help of magnets and quadrupole lenses and finally hit the target, where they induce nuclear reactions. Detection of the reaction products (particles and γ -rays) and the measurement of their energies, intensities and angular distributions enables the deduction of properties of nuclear levels.

A two stage (tandem) accelerator has a similar design as a single stage accelerator, but the ion source is situated outside the tank and produces negatively charged ions, which are accelerated towards the positive high voltage electrode. When the ions reach the high voltage electrode, they pass through a foil, where they are stripped of some electrons. Having become positively charged in this way, the ions are accelerated once more. The advantages of a tandem accelerator are:

- (i) it is possible to reach higher beam energies, since the ions are accelerated twice and
- (ii) since the ion source is situated outside the tank, one has much more freedom in its construction and can make many different kinds of ions.

2.2 Event-mode recording

Charged particles from nuclear reactions are often detected with Si surface-barrier detectors and γ -rays with Ge(Li) detectors. The analogue pulses from each detector, which are proportional to the energy dissipated in the detector, are digitized (after amplification) in analogue-to-digital converters (ADC:s). Each coincident event, e.g. a particle and a γ -ray detected at the same time (within ~ 10 ns), after digitization is routed to a computer and written on magnetic tape. This technique is called on-line event-mode recording.

In a reaction of the type $A(a,b\gamma)B$ the spectrum of the outgoing particles b reflects the level scheme of the final nucleus B , i.e. each level or group of levels in B is seen as a peak in the particle spectrum. By setting a gate on a peak in the particle spectrum and looking for the γ -ray spectrum coincident with it one can obtain very simple spectra showing the decay of only a few levels.

When the on-line data collection is finished, the experiment can be re-played as often as is desired by reading the tapes with events back into the computer. New spectra may be generated in accordance with the gates given by the experimenter. This process is called off-line sorting.

2.3 Doppler-shift-attenuation measurements

In the Doppler-shift-attenuation (DSA) method γ -ray spectra are measured at several angles θ_γ relative to the beam axis. Gamma-rays of energy E_o emitted by a moving excited nucleus are Doppler shifted, the shift ΔE to a first approximation being proportional to the velocity v of the nucleus: $\Delta E = E_o \cdot \frac{v}{c} \cdot \cos\theta_\gamma$. Measurement of the attenuation $F(\tau_m) = \Delta E / (E_{full} - E_o)$, where $(E_{full} - E_o)$ is the shift expected for infinitely short lifetime, yields information on the mean lifetime τ_m of the decaying level if τ_m is comparable to the slowing-down time of the nucleus in the backing material. The slowing-down

process is thus used as an internal clock for the decay of the excited state. The DSA method with nuclei stopping in solid materials can be used to measure lifetimes in the range 5 fs to 5 ps.

The disadvantages of this method are that the slowing-down process is not perfectly known, especially at low recoil velocities, and that local irregularities in the backing material may influence the result. Both these disadvantages can be overcome by using inverse reactions in which very light nuclei (e.g. ^1H , ^2H , ^3H or ^4He) implanted in some solid material are bombarded with heavy ions [1], a method which gives relatively high recoil velocities ($v/c \approx 5\%$).

2.4 Angular correlation measurements

Angular correlation techniques have been used since 1947 [2] to determine spins of excited states in nuclei. The theory of angular correlations is older, and can be derived using group theory, Racah algebra and density matrix formalism. For simple cases, however, the theory can be made plausible by more elementary means starting from Maxwell's equations and explicit summing over the magnetic substates [3].

Angular correlation measurements in the present application consists of measuring γ -rays at several angles in coincidence with particles detected with an annular detector placed near 180° (or 0°) relative to the beam axis. The beam axis is a symmetry axis and, if we choose the z-axis in this direction, the magnetic substates of the final nucleus will be symmetrically populated (alignment), i.e. if the probability of populating the substate α is $p(\alpha)$ we have: $p(\alpha) = p(-\alpha)$. If the outgoing particles from a reaction $A(a,b)B$ are detected near 0° or 180° ($\theta_b \approx 0^\circ$ or 180° , collinear geometry) only those magnetic substates will be populated for which $|\alpha| \leq J_A + s_a + s_b$, where J_A , s_a and s_b are the

spins of the target nucleus, the incoming particle and the outgoing particle, respectively. This rule is easily understood from the definition of the z-axis: Since the incoming and the outgoing particle move along the z-axis they can carry no z-component of orbital angular momentum. For the $^{26}\text{Mg}(\alpha, p\gamma)^{29}\text{Al}$ reaction (paper III) the rule gives $|\alpha| \leq 1/2$, and thus $p(-1/2) = p(1/2) = 1/2$ since $\sum_{\alpha} p(\alpha) = 1$. The population parameters are thus unambiguously determined. If $J_A \neq 0$ or the outgoing particles are detected far from the z-axis the population parameters are not unambiguously determined, and they can only be calculated if the reaction mechanism is known.

The angular distribution of γ -rays from an aligned state depends on the degree of alignment (expressed by the statistical tensors), the spins of the initial and final states and the multipole mixing ratio δ of the transition. Not even in the present case, in which the alignment is perfect (only the lowest substates populated) and there is only one continuous physical parameter (δ), does the angular distribution always give unique solutions for the spins and δ involved. Hypotheses can be rejected if they give improbably large transition strengths (larger than the recommended upper limits of ref. [4]), but very often one is left with two possible solutions [5]. These inherent ambiguities can sometimes be resolved by measuring γ - γ correlations or linear polarization.

2.5 Computer programs

To facilitate the analysis of complex γ -ray spectra a FORTRAN program ANNLIIS [6] has been written. This program automatically locates peaks in a spectrum and determines their areas. The peaks are located by application of a cross correlation function [7] (CCF). A point of this CCF is calculated by multiplying the spectrum channel by channel by a Gaussian with a width equal to the width of the peaks in the spectrum, adding up the result and subtracting a background. Then the search Gaussian is displaced one channel, the next point of the CCF is

calculated and so on. The CCF contains the enhanced structure of the original spectrum: where there is a peak in the original spectrum the CCF becomes positive, where there is no peak the CCF becomes negative. The position of a peak is defined as the first moment of the positive part of the CCF. By giving a number of calibration energies the peak positions can be converted into energies by means of a polynomial (usually of order ≤ 3) fitted with a least-squares method through the calibration points.

Peak areas are calculated after subtraction of an exponential baseline fitted through the areas on each side of the peak. By giving the relative efficiency function of the detector, relative intensities can be calculated by the program.

The main disadvantage of the program ANNLS is that it cannot handle composite peaks. This problem does not occur in the peak fitting program GAUSS [8] imported from Utrecht. The Utrecht version is used in an interactive way on a small computer. This version has been modified to be run as a batch job on the UNIVAC 1108 computer in Lund.

The program GAUSS uses a least-squares method to fit a parabolic background and up to 6 skewed Gaussians (Gaussians with exponential low-energy tails) to a part of a spectrum. The output gives the peak positions, the peak areas, width of the peaks, χ^2 of the fit (a measure of the goodness of the fit) and also a line-printer plot of the fit.

A program CHI2 has been written for the analysis of angular correlation data. It calculates the theoretical angular distribution of a transition $J_i \rightarrow J_f$ for given values of J_i , J_f , the mixing ratio δ and the population parameters $p(1/2)$ and $p(3/2)$ ($p(0)$ and $p(1)$ for integral spin). The theoretical angular distribution is fitted to experiment by varying the

normalization and the χ^2 value of the fit is calculated. The value of χ^2 is plotted as a function of δ on the line-printer for visual inspection and rejection of spin hypotheses. The statistical tensors and angular distribution coefficients needed for the calculation of the theoretical angular distributions are calculated with subroutines for 3-j and 6-j symbols.

Among other programs written for the UNIVAC 1108 computer are a versatile program for plotting spectra with a Calcomp plotter, programs for calculating attenuation curves (F as a function of τ_m) for DSA measurements, reaction kinematics with relativistic corrections [9] and theoretical γ - γ angular correlations for arbitrary geometries [10].

3. SUMMARY OF EXPERIMENTAL WORK

3.1 Paper I

Because of the complexity of states at high excitation energy the resonances observed in (p,γ) reactions were for a long time used only as well-defined initial states for the study of the subsequent deexcitation to bound states. This situation changed, however, when it was realized that certain resonant states, the so-called isobaric analogue resonances (IAR:s), had a close relationship to low-lying states in the adjacent isobaric nucleus and thus had a rather simple structure. The IAR:s usually stand out in the yield curve as prominent peaks on the "grass" generated by hundreds of "normal" (T-lower) resonances. Sometimes, however, the strength of an IAR is shared between several levels and this makes the IAR less prominent.

Paper I reports a study of the decay of the $E_p = 1658$ keV resonance in the $^{44}\text{Ca}(p,\gamma)^{45}\text{Sc}$ reaction. This resonance is a member of the split analogue of the $E_x = 1.90$ MeV; $J^\pi = 3/2^-$ state in ^{45}Ca . The experiment was performed with protons from the University of Lund 3 MV VdG. Gamma-ray spectra were measured at two angles, $\theta_\gamma = 55^\circ$ and 90° . This yielded branching ratios and excitation energies for levels up to 3 MeV. For some levels, the feeding from the $J^\pi = 3/2^-$ proton capture state and the subsequent decay to levels with known J^π could be used to impose J^π restrictions. The observed decay of the proton capture state indicates that the anti-analogue state is fragmented. (The anti-analogue state lies below the analogue state and has the same wave function but with an isospin of one unit less.) Hence the M1 transition strength is distributed over several transitions, in contrast to the very strong analogue to anti-analogue transitions observed in the 2s1d-shell [11].

3.2 Paper II

Levels of ^{24}Na up to 4.2 MeV excitation energy were investigated with the $^{23}\text{Na}(d, \gamma)^{24}\text{Na}$ reaction. Part of the experiment was performed in Lund with the 3 MV VdG and part in Utrecht with the 6 MV tandem VdG. Deuteron bombarding energies of 2.5 and 2.8 MeV were used.

Before the experiment was started an interface between 2 ADC:s and the IBM 1800 computer in Lund was designed and built. Programs for on-line data collection and off-line sorting were also written, so that on-line two parameter event-mode recording of proton- γ coincidences was possible.

Protons were detected at $\theta_p = 155^\circ$ in the vertical plane through the beam and γ -rays were detected at $\theta_\gamma = 90^\circ$ in the horizontal plane. Excitation energies of a number of levels were obtained.

For measuring branching ratios a collinear geometry with an annular Si detector near $\theta_p = 180^\circ$ and a Ge(Li) detector at $\theta_\gamma = 55^\circ$ was used. This part of the experiment was performed in Utrecht using an event-mode data collection system [12] on a CDC 1700 computer.

The experiment yielded excitation energies and branching ratios for 27 levels, two of which, at $E_x = 3.94$ and 4.20 MeV, were observed for the first time.

Recently Smulders [13] and Keverling Buisman and Smulders [14] have published results from investigations with the $^{23}\text{Na}(d, \gamma)^{24}\text{Na}$ reaction. Their results, which also include DSA lifetime measurements, are in good agreement with the results of paper II.

3.3 Paper III

The $^{26}\text{Mg}(\alpha, \gamma)^{29}\text{Al}$ reaction was used to investigate ^{29}Al levels up to 6 MeV excitation energy. The experiment was performed with α -particles from the Utrecht 6 MV tandem VdG. Alpha-particle bombarding energies in the

range 14.2 to 18.0 MeV were used. The data were processed by a multiparameter data acquisition system [12] on a CDC 1700 computer.

Excitation energies of 27 levels were determined and a new level at $E_x = 5.25$ MeV was found. The DSA method with ^{29}Al ions stopping in a Au backing was used to determine mean lifetimes of 14 levels and upper limits for 7 levels. From proton- γ angular correlation measurements with a collinear geometry branching ratios, some J^π assignments and multipole mixing ratios could be inferred. Gamma-ray spectra were measured at five angles with an effective collection time of 16 h per angle, the total measuring time being 5 days.

The following J^π assignments were made with the 0.1% probability criterion (meaning that there is less than 0.1% probability that a correct J^π possibility is excluded): $J^\pi(2.22) = 3/2^+$ and $J^\pi(3.18) = 5/2^+$. In addition several J^π limitations were inferred and circumstantial evidence for a ground state rotational band, $J^\pi(0) = 5/2^+$, $J^\pi(1.75) = 7/2^+$, $J^\pi(3.58) = 9/2^+$ and $J^\pi(5.86) = 11/2^+$, was given.

The experimental results were compared with calculations by De Voigt et al. [15] who performed a shell model calculation in a truncated $1d_{5/2} 2s_{1/2} 1d_{3/2}$ configuration space with the modified surface delta interaction as an effective two-body interaction. The agreement with experiment was on the whole good, except for the excitation energies and a few transition strengths.

Since the publication of paper III the assignment $J^\pi(2.22) = 3/2^+$ has been confirmed (Williams et al. [16]) by linear polarization measurements with the $^{26}\text{Mg}(\alpha, p\gamma)^{29}\text{Al}$ reaction.

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Nuclear physics research with complex equipment and long measuring times must necessarily be a team-work. In this sense I have been fortunate to have had very able and enthusiastic collaborators, and I want especially to thank Dr Jan Tillman for many years of close and inspiring co-operation.

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Finally, to all those of the scientific, technical and administrative staffs in Lund and Utrecht who in many ways have helped me in the course of my work I want to say:
"Tack så mycket" / "Dank U wel" / Thank you very much!

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ERRATA

+/- = from top/from bottom

	Page	Line	Change	Into
Paper I	189	7 ⁺	^{44}Ca	^{45}Ca
	190	8 ⁺	$^{42}\text{Ca}(\text{p}, \alpha\gamma)^{45}\text{Sc}$	$^{42}\text{Ca}(\alpha, \text{p}\gamma)^{45}\text{Sc}$
	192	6 ⁻	$^{40}\text{K}(\beta^+)$	$^{40}\text{K}(\text{EC}\gamma)$
	196	fig. 4	The arrow ending at the level 1433.4 should end at the level 1555.1. The arrow ending at the level 2352.1 should also end at the level 2341.2. The level 1236.4 has $J^\pi = 11/2^-$	
	200	12 ⁺	2303.7	2303.8
	201	8 ⁻	^{45}Ca at 1904 keV has	^{45}Ca has
	201	7 ⁻	(p, p')	(p, p)
	204	fig. 8	The level 12.4 has	$J^\pi = 3/2^+$
Paper II	459	fig. capt. labeled		labelled
Paper III	285	13 ⁺	mixing ratios, s.	mixing ratios.

